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HOLOGRAPHIC INTERFEROMETRIC FRINGE INTERPRETATION

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Prepared for

National Aeronautics and Space Administration
George C. Marshall Space Flight Center
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Current literature concerning the measurement of small displacements by laser holographic technique has been reviewed. It has been found that existing theories are extremely difficult, if not impossible, to apply to any realistic nondestructive testing conditions in which the geometries of the objects are complex and the 3-dimensional displacements are irregular. Therefore, an experimental approach toward the interpretation of the correlation between real-time holographic fringe patterns and the small displacements on a flat test plate has been adopted here. Preliminary results showed that the present method is feasible for the quantitative interpretation of the fringes as well as the calibration of the mobile HNDT system.

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I. INTRODUCTION

Recently, laser holographic nondestructive testing (HNDT) technique has been proved to be very sensitive and effective in the detection of debonds in ceramic-epoxy-fiberglass composite structures [1]. The debonds would appear as surface deformation after the structure was loaded by an appropriate external stress. Either double-exposure or real-time interference fringe patterns would be able to reveal the existence of any surface deformation on the order of a quarter of the radiation wavelength of the laser. Small displacements on the surface would cause nonuniformity or irregularity in the interference patterns [2].

To understand the experimental results, it is important to interpret the fringe patterns. Haines and Hildebrand have presented a detailed theory for the interpretation of the interference phenomenon. Sollid [3] has discussed how either a single hologram or multiple holograms could be used in the measurement of small static displacements on a diffusely reflecting surface. However, in any practical situation these theories are found to be difficult, if not impossible, to apply.

Very lately, Bellani and Sona [4] have reported the method of scanning a double-exposure hologram and counting the number of fringes on the real image of the object. The method worked well with simple motions of the object, but it was not applied to any complex displacements. Since the principle of the method was based on the small dis-

placement of the object from one point to another only, it is doubtful that the method can be used to interpret any complicated movement of the surface.

Because there is no simple theory which can interpret the fringe variations of any complicated surface displacement thus far, we propose that an experimental approach be employed.

The purpose of this report is to discuss the design of the test plate as well as some preliminary results of the experiment. A theoretical discussion of the HNDT system and the basic principles of interferometry will be given in Section II. The experimental setup and results will be discussed in Section III. Section IV provides the conclusion and suggestions for future investigations.

II. THEORETICAL DISCUSSION

The Composite Mobile HNDT System

The composite mobile HNDT system is a variable sensitivity system. The main advantage of this kind of system is that all methods of HNDT can be accomodated with basically the same holographic arrangement. The system can be illustrated by Figure 1. Configuration No. 1 of Figure 1 may be described below. Laser light is incident on the field mirror assembly which contains a spatial filter and a beam splitter. This assembly or unit is translatable to the left along the path Sb. The reflected portion of the radiation is made incident on the micrometer translatable object in such a direction as to make an angle

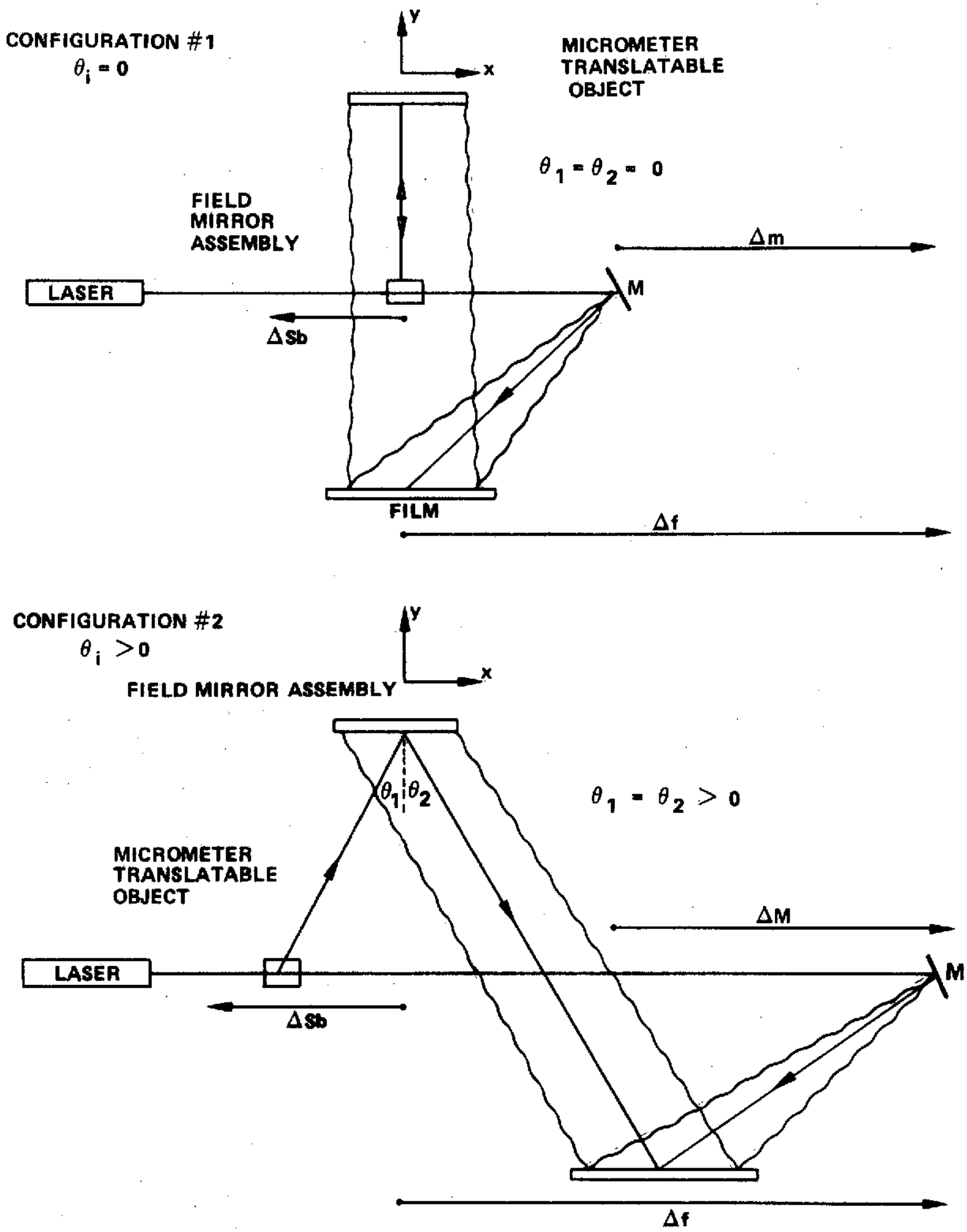


FIGURE 1. COMPOSITE MOBILE HOLOGRAPHIC NONDESTRUCTIVE TEST SYSTEM.

$\theta = 0$ with the perpendicular bisector of this object. This radiation is then turned antiparallel to itself where it passes onto the film recorder. The film recorder is itself translatable to the right along the path Δf. The radiation transmitted through the field mirror assembly is incident on mirror M, which is itself translatable to the right along path Δm. From here it is turned to be incident on the film recorder and interferes with the object beam.

Configuration No. 2 may be traced in a similar fashion, except that the object beam makes some angle $\theta > 0$ with the perpendicular bisector of the object.

The system is composite because one needs to only slightly manipulate three components (field mirror assembly, mirror M, and film recorder) to change from one method of HNDT to another. It is not necessary to establish a new geometry in order to perform the various HNDT methods. The system is mobile because all of the optical components are mounted on a precalibrated rigid table and may be locked in any position along their translatable paths. The system has variable sensitivity (which affords the composite structure) by virtue of the control over the angle θ which the object beam makes with the perpendicular bisector of the object.

The principle of the double-exposure technique has shown that zeros indicating the presence of fringes occur for the movement of the object for a distance

$$m = \frac{(2n - 1)\lambda}{2(\cos\theta_i + \cos\theta_s)} \qquad (1)$$

where n is the number of fringes.

Consider the case of $\theta_1 = \theta_2 = 0$, and $\lambda = 6328\ \mathring{A}$ for a He-Ne laser; then Equation (1) becomes

$$m = (2n - 1)\ \frac{\lambda}{4} = (2n - 1)\ \frac{6328\ \mathring{A}}{4} = (2n - 1)\ 0.1582\mu m\ ,$$

which says that in order to obtain one fringe on the object, the movement of the object (in the same direction) must be as great as 0.6112μm. While both of these movements are small, their relative values differ by about one-half order of magnitude. This provides an indication of the variation of sensitivity of this system by the minute adjustment of three single components on a precalibrated mobile table. The table is precalibrated in terms of the desired sensitivity.

Fringe Formation in the HNDT System

In the application of holography to the field of nondestructive testing, it is generally agreed that there are three kinds of techniques: real-time, double-exposure, and time-averaged. Nevertheless, the basic principle with regard to the interference fringe formation is the same for all three techniques. This principle can be illustrated by the real-time testing case as discussed below. The application of this principle to the other two cases will follow.

As mentioned in the last section, the present holographic nondestructive testing system is based on the principle that extremely small displacements on the surface of an object, on the order of .15μm (if a He-Ne laser is used), can be detected by the difference of the interference fringe patterns as viewed through the hologram on a real-

time basis. The fringe patterns will vary according to the small displacement on the surface because there is a phase difference between the two path lengths, one is the light from a point of the virtual image of the object and the other is from the same corresponding point on the real displaced object. The phase difference can be simply analyzed with the help of Figure 2.

Where in Figure 2, S represents the laser light source, p and p' represent, respectively, the same spot on the virtual image of the object and the displaced object. H is a point on the hologram. It can be easily seen that the path length L_1 and L_2 may be written in terms of the various distance vectors as follows:

$$L_1 = |\vec{pS}| + |\vec{pH}|$$

$$= (\vec{pS} \cdot \vec{pS})^{1/2} + (\vec{pH} \cdot \vec{pH})^{1/2} \tag{2}$$

and

$$L_2 = (\overrightarrow{p'S} \cdot \overrightarrow{p'S})^{1/2} + (\overrightarrow{p'H} \cdot \overrightarrow{p'H})^{1/2} . \tag{3}$$

The phase difference θ is defined as

$$\theta = (2\pi/\lambda) \text{ X } (L_1 - L_2) , \tag{4}$$

where λ is the wavelength of the light.

Through some arithmetic manipulations and an assumption that the displacement $\overline{pp'}$ is always much smaller than either $\vec{pS}$ or $\overline{pH}$, we obtain a simplified expression [2] for $\Delta\theta$:

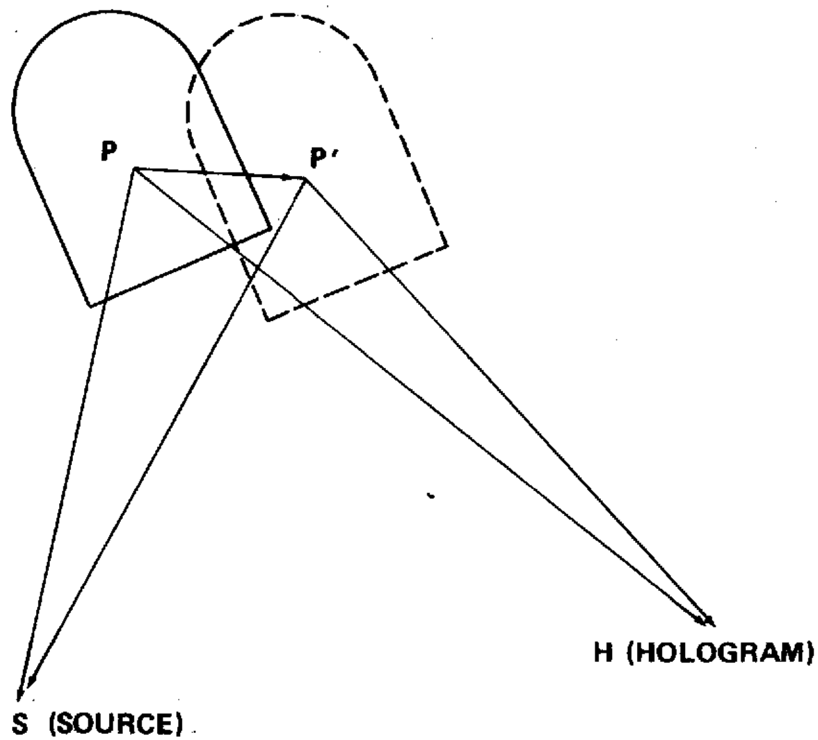


FIGURE 2. CREATION OF THE PHASE DIFFERENCE $\Delta\theta$

$$\Delta\theta = (2\pi/\lambda) \times [pS/(\vec{pS} \cdot \vec{pS})^{1/2} + pH/(\vec{pH} \cdot \vec{pH})^{1/2}] \cdot \vec{pp'} \,. \qquad (5)$$

The above equation represents a general and basic relation necessary for the analysis of the small displacements in any holographic interferogram of a diffusely reflecting surface.

In the application of this principle to explain the double-exposure technique, all we have to do is to consider the interference between two virtual images displaced from each other.

If we apply Equation (5) to the three-dimensional case just as in our nondestructive testing system where we have no a priori knowledge of the displacement vector, theoretically speaking, two methods are available for the determination of the displacement vector $\vec{pp'}$ based on the observed fringe patterns. If zeroth-order fringes are identifiable, a multiple hologram method [3] may be used. If, on the other hand, the zeroth-order fringes cannot be localized, a single hologram technique must be employed. Very recently, Bellani and Sona [4] reported that they have applied a new scanning method which was able to count the number of fringes from the real image of a double-exposure hologram. The method was not tested for the case of any complicated motion of the object or any object with irregular or curved surfaces as in realistic testing situations. In addition, the principle of this method is also based on Equation (5) above, which has the disadvantage of only considering the displacement from one particular point to the other. Continuous phase change caused by the displacement of a small region on the surface is not expressible by this equation. Therefore, we

conclude that all of the existing methods of fringe interpretation are extremely difficult, if not impossible, to apply in a realistic nondestructive testing system. To overcome the practical difficulties, the following experimental studies have been carried out.

III. EXPERIMENT

Test Plate Design

An aluminum test plate of size 15 cm by 15 cm was fabricated. A 5 x 5 matrix of equally spaced holes was drilled through the plate. The plate, which was sitting on a heavy metal stand, is shown in Figure 3. The holes are used for the positioning of thin metal foils as shown by the two dark pieces in the upper half of the plate. One piece of the foil (the larger square-shaped one) was connected from the back to an electric power source. The purpose of the connection is to make current go through the metal foil and return from the aluminum plate when contact is made between the foil and the plate. Movement of the thin foil can be controlled by the ohmic heating of the current through the thin foil.

The HNDT System

The test plate described above was then placed in the sample's position of the HNDT system as depicted in Figure 4. The power supplied can be controlled by a variac and the resistance R in the circuit. The laser used was a Spectra-Physics Model 125 He-Ne gas laser. One of the most important parameters in the system is the

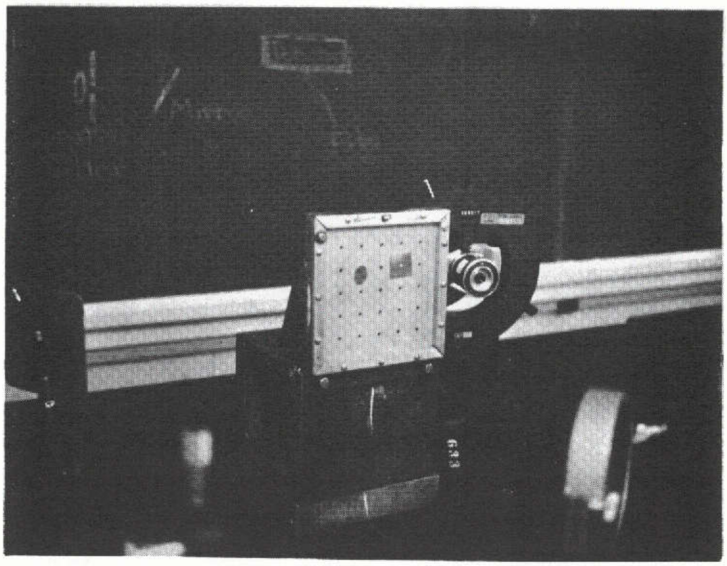


Figure 3. Test plate sitting on a heavy metal stand.

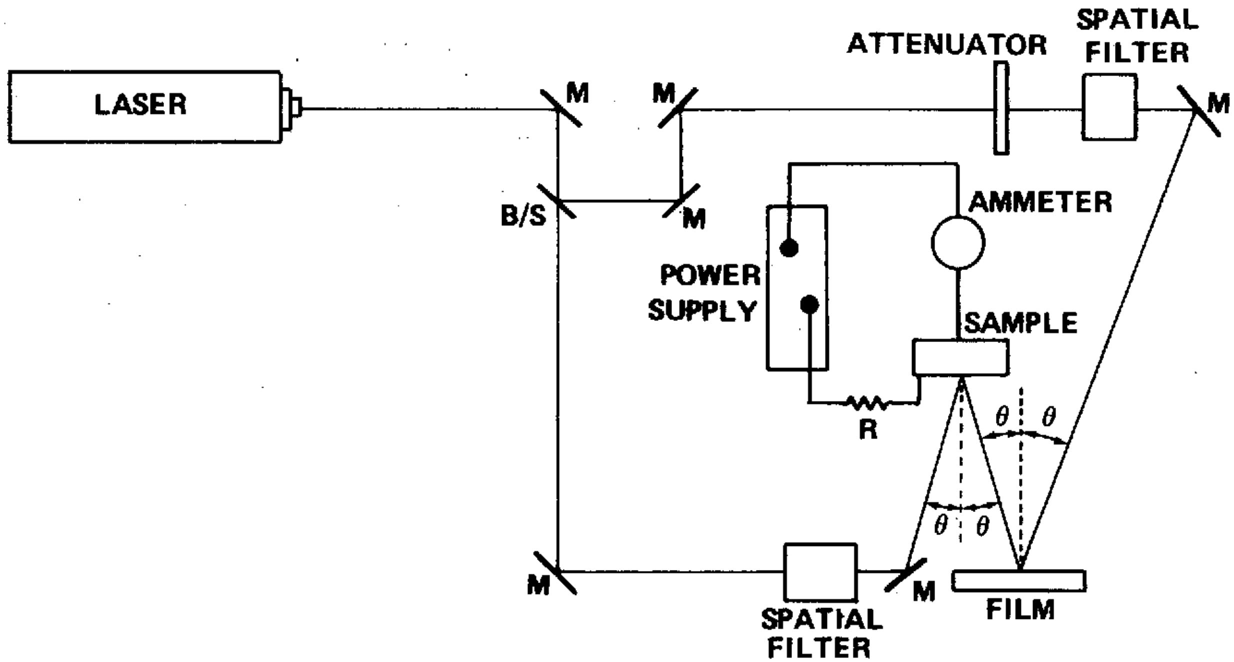


FIGURE 4. THE HNDT SYSTEM DIAGRAM

angle θ. Because, as previously explained, the sensitivity of the system depends on this angle.

An overall view of the completed and aligned system is shown in Figure 5. All the components are placed on the top of the table, which is a Modern Optics air-suspended stable table. The He-Ne laser is supported beneath the table and, hence, is not visible in this picture. The table has a resonance frequency of less than 1 Hz so that it is particularly suitable for the HNDT work.

Experimental Result

The experiment has been carried out by setting the angle $\theta = 12.6$ deg as shown in Figure 4. The small piece of thin foil was fixed to the upper right corner and the larger square foil was placed at the lower left corner; this position is referred to as position A. A hologram was taken and replaced into the Jodon Model MPH-45 X-Y-Micropositionable Photographic Plate Holder. A sequence of Polaroid pictures was then taken while the current through the circuit connecting the square metal foil and the test plate was varied. The corresponding real-time fringe variations are shown in Figure 6.

Part (a) of Figure 6 shows the interference fringes between the virtual image and the object as viewed through the hologram immediately after the replacement. These fringes are thought to be associated with the shrinkage of the emulsions of the holographic plate or the inability to replace the plate exactly to the position in which the hologram was taken. The current i was set to zero at

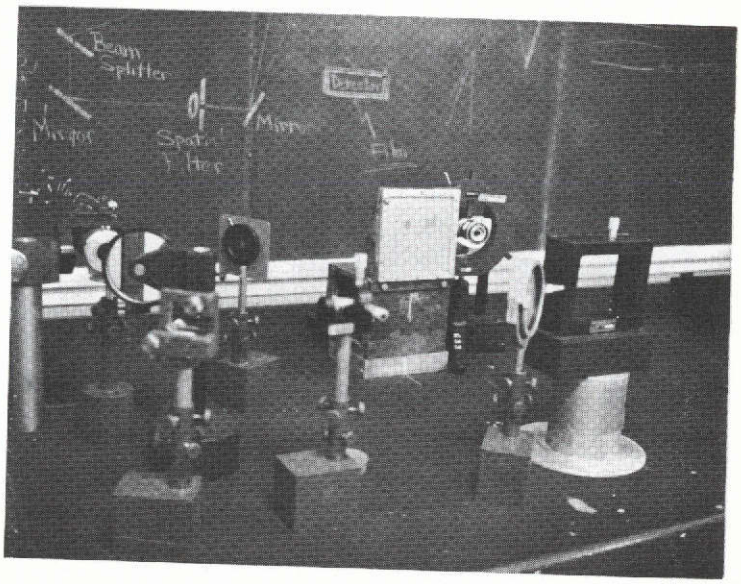
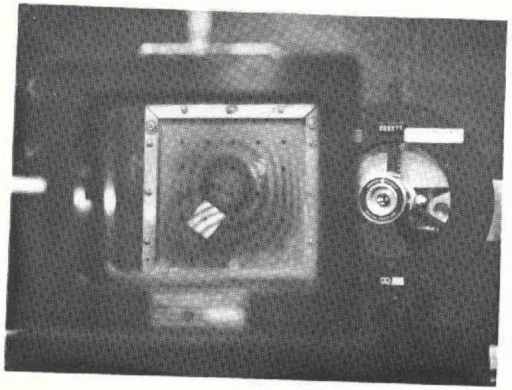
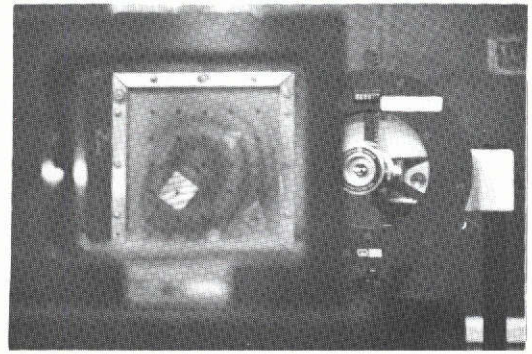


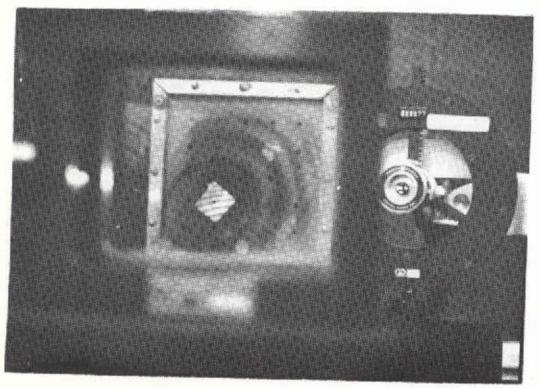
Figure 5. Completed HNDT system.



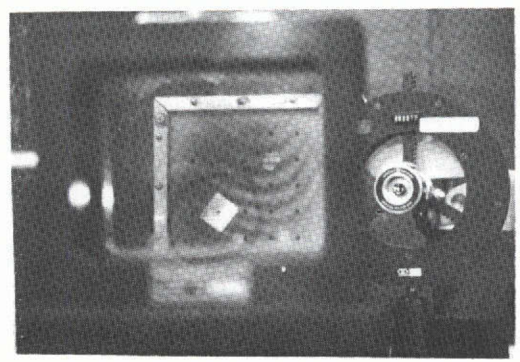
(a) Current i=0



(b) i=40ma after 5 minutes



(c) i=40ma after 8 minutes



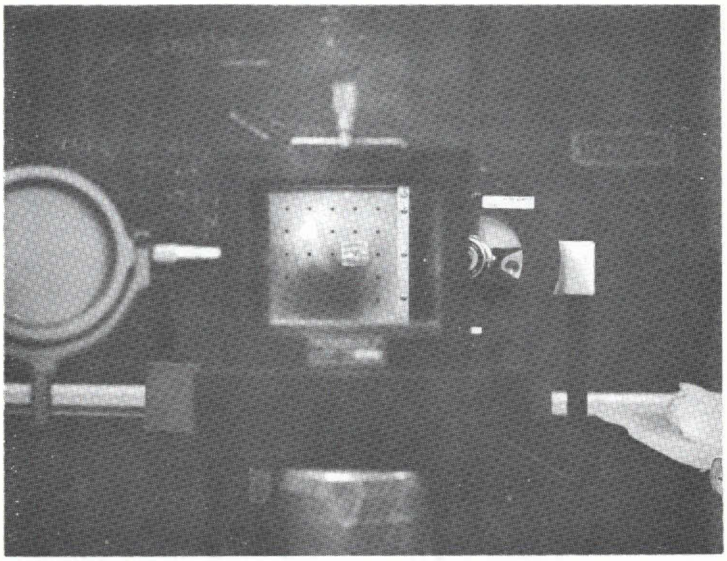
(d) i=50ma after 3 minutes

Figure 6. The effect of current on the fringes for position A.

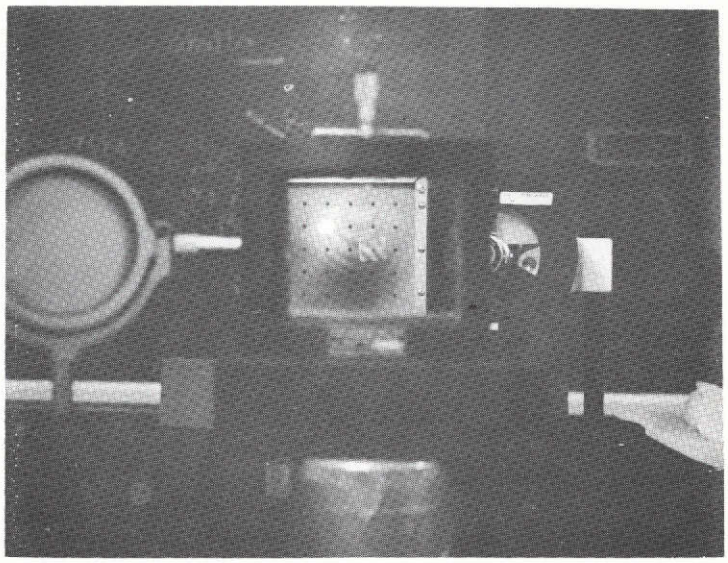
this moment to correspond to the condition under which the hologram was taken. The picture in Figure 6(a) may, therefore, be considered as a reference for position A. After we applied a current of 40 ma for 5 minutes, the fringe pattern changed and the result was recorded and shown in Figure 6(b). Notice the increment of the number of fringes increased to 6 after 8 minutes of 40 ma of current. After that, a steady state was reached, and the number of fringes did not increase any more at this current level. The result is shown in Figure 6(c). The current was increased to 50 ma and held for a period of 3 minutes; the resulting fringe pattern is depicted in Figure 6(d). The number of fringes on the square foil increased to 10. The effect of electric heating is, therefore, clearly demonstrated by these pictures.

Two other phenomena in these pictures are worth mentioning. The number of fringes on the smaller foil essentially did not change because there was no electric heating applied directly to this foil. Consequently, the fringe patterns on this small foil served as a good contrast in comparison to those shown on the large square foil. On the other hand, the fringes on the test plate did first reduce in number then vary in shape from (a) to (d). This probably is due to the gradual drying of the emulsions of the hologram.

Other data with the small foil placed on the upper left corner are depicted in Figures 7, 8, and 9. The (a) part of each of these figures shows the reference for each of the positions. The positions in Figures 7, 8, and 9 are called B, C, and D respectively, for the sake of identification. The (b) part of each figure indicates the

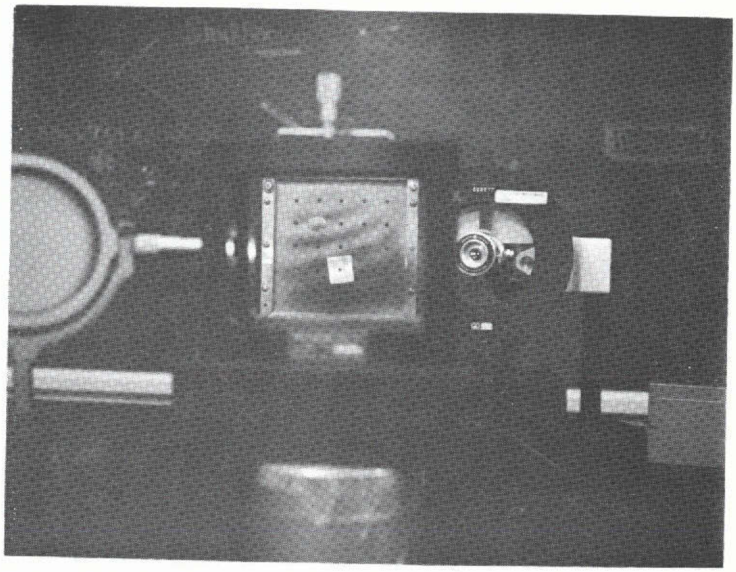


(a) Reference i=0

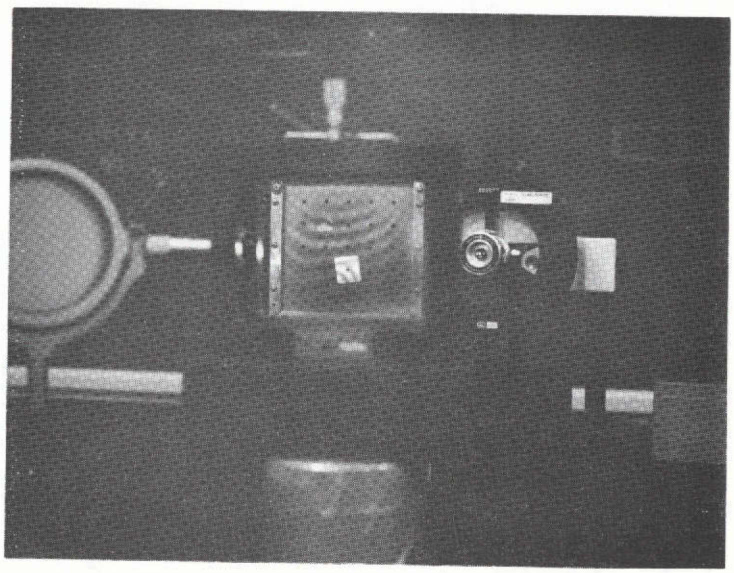


(b) After 2 minutes of i=50ma

Figure 7. Fringe variations with current for position B.

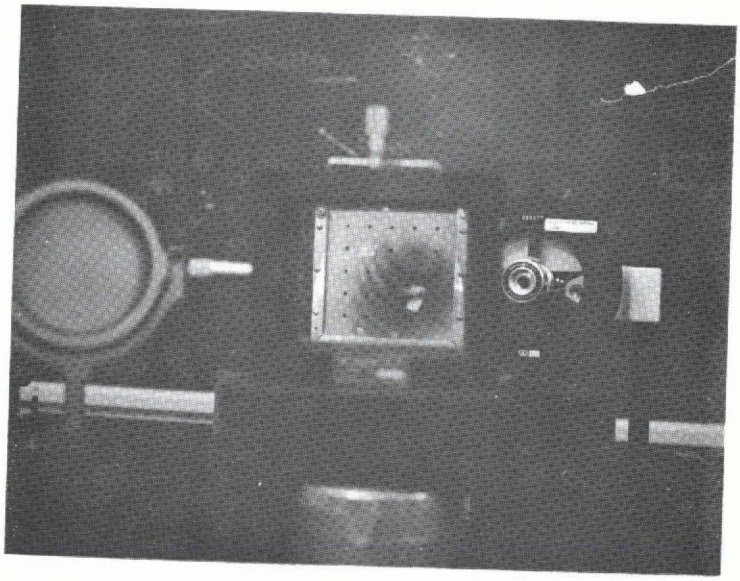


(a) Reference, i=o

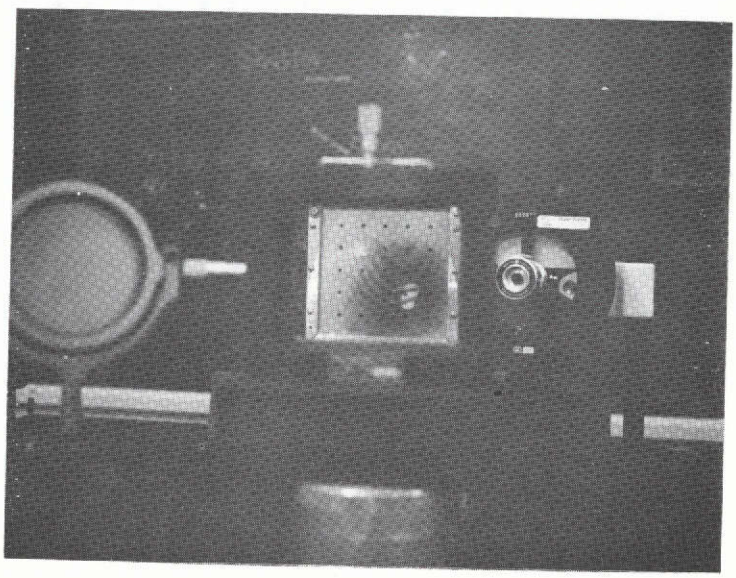


(b) After 2 minutes of i=50ma

Figure 8. Fringe variations with current for position C.



(a) Reference, i=o



(b) After 2 minutes of i=50ma

Figure 9. Fringe variations with current for position D.

fringe variation after the application of 50 ma for a period of 2 minutes. Similar phenomena as those shown in Figure 6 also appeared in these pictures.

IV. CONCLUSIONS AND SUGGESTIONS FOR FUTURE WORK

The preliminary results discussed in the last section were mainly in a special case of the system setup with $\theta = 12.6$ deg. This particular angle was chosen so that direct application of the results to the holographic nondestructive testing of the Space Shuttle main engine at the Space Sciences Laboratory at NASA, Huntsville, could be made. The results have demonstrated the feasibility of the idea that the matrix-type displacement could be used for the calibration of the mobile HNDT system.

One improvement of the system is to design and fabricate a system such that any displacement can be controlled by a highly accurate and sensitive micrometer. In this way, quantity data of the distance moved can be recorded and its correlation to the fringe variations can be established. Once this step is finished, angular values of θ from 0 to 75 deg at discrete separations should be set for the system and detailed calibrations of the system should be worked out similar to the example given in the last section.

After the project for the flat test plate is finished, work should be extended to cases of other geometries such as cylindrical plate, which is of more resemblance in shape to that of the main Space Shuttle engine.

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